Study on the Influence of Material Inhomogeneity on Characteristics of Ultrasonic Wave Propagation

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It is required to maintain the durability of concrete structures from the viewpoint of the proper control of maintenance. Thus, it is necessary to evaluate the soundness of the structures. The ultrasonic method which is one of nondestructive tests is tried to use as an evaluation method. In the case of the object of which density is high and its distribution is homogeneous, the ultrasonic can detect defects correctly. However, a concrete is inhomogeneous, and the wave spreads intricately if it comes to a crack or a discontinuous portion. Therefore, the limit and usefulness of applicability of the ultrasonic method are indefinite. In order to apply the ultrasonic method to concrete structures, it is necessary to grasp the influence of the properties of the concrete on the propagation of the wave. In this study, numerical analyses are conducted with considering the inhomogeneous of the concrete to check the applicability of the ultrasonic to the concrete.

1. INTRODUCTION

In the maintenance management of infrastructures such as a road and a bridge, visual inspection is mainly conducted. It is general to inspect them in detail in finding the damage of the infrastructures\(^1\),\(^2\). In order to grasp the damage condition inside a structure, the nondestructive test which enables us to inspect without any damage to the structure is frequently utilized\(^3\),\(^4\). However, an evaluation depends on an inspector's skill or is influenced by an inspection method.

Since the inspection by the ultrasonic method which is one of nondestructive tests is not dependent on an inspector's experience, it is expected as a degradation evaluation method. The method is classified into two broad categories: an echo method and a transmission method. The transmission method determines the extent of damage by the damping level of ultrasonic associated with defects or compositions. On the other hand, the echo method detects defects by the difference in reflection at a defect or a boundary surface. In the transmission method, the transmitter and receiver of an ultrasonic are settled on opposite surfaces across a object. Meanwhile, in the echo method, they are settled on a same surface. Although a structure such as a bridge pier can be inspected by the transmission method, it is difficult to inspect structures such as a nuclear power plant building or a tunnel structure by the transmission method. Thus, it is expected that the echo method is applied to the inspection for a nuclear power plant building or a tunnel structure.

Whereas there are number of researches on the application of the transmission method to the concrete\(^5\),\(^6\) which is heterogeneous material, there are few ones on the application of the echo method. Furthermore, the application of the echo method is restricted within the evaluation of the crack depth and the determination of
rebar position. In this study, finite element analyses are conducted with considering the degradation so as to clarify the influence of degradation and discuss the application of the echo method to the degradation evaluation of heterogeneous material.

2. PROPAGATION ANALYSIS OF ULTRASONIC

2.1 FINITE ELEMENT ANALYSIS

Since an ultrasonic is an elastic wave, the object targeted in this study is assumed to be an elastic material. There are various methods for a wave propagation analysis, for example, the numerical integration scheme in which a solution is derived by the numerical integration of equilibrium equation at every infinitesimal time, or the mode polymerization method in which the linear response of multi-degree-of-freedom system is expressed by the superposition of every order mode of eigen frequency. In this study, the numerical integration scheme is employed, and Newmark-β method which is most widely used in earthquake response analysis is chosen among a number of numerical integration schemes.

2.2 OUTLINE OF ANALYSIS

The ultrasonic propagation is analyzed as a target for the experimental concrete specimen in which alkali-aggregate reaction is accelerated (see, Fig.1). The echo method is applied to the specimen in changing the distances between transmitter and receiver (d in Fig.1); d=150mm, 250mm, and 400mm. For detail, please see the reference. Fig.2 shows the response waveform of the experiment. In the figure, there are two types of wave; one is a direct wave and another is an echo wave. The direct wave propagates on the specimen surface and arrives at the receiver. On the other hand, the echo wave reflects on the opposite side of transmitter and arrives at the receiver. The longitudinal and cross section views of analysis model are shown in Fig.3. A concrete structure is the composite material which consists of cement hydration product, aggregate, void, etc. There is a possibility that the ultrasonic propagation is affected by these composites. Thus, in this study, it is presupposed that the analysis model consists of two elements, mortar and coarse aggregate elements, with simplicity paramount in thinking. An example of both the elements distribution in the analysis is shown in Fig.4. The shape of the ultrasonic transducers, the transmitter and the receiver, used in the experiment is true circle and their diameter is 40 mm. Since it is a little bit messy to make finite element meshes in a circle, the
area of both the transmission and reception in the analysis is transposed to quadrangle in equaling to the experimental area. The Poisson ratio and mass density of the experimental specimen are not obtained. Thus, the general values of concrete are adopted (see, Table 1). According to the combination design of the experimental specimen, the volume fraction of coarse aggregates is set to 50%\(^{40}\). Macroscopic elastic modulus of the specimen is set to 35,000N/mm\(^2\) by the dynamic loading test. Thus, the elastic moduli in sound condition of two elements, the mortar and coarse aggregate elements, are set as shown in Table 1. The distribution of coarse aggregate elements is located at random with a random number generation program. The number of analysis steps is examined so that they don’t have influence on analysis accuracy. In consequence, it is set to 400 steps in 0.0003 second. The half-wave length of sine wave shown in Fig.5 is employed as the ultrasonic referring to the input wave of the experiment. The frequency of the wave is set to 50 kHz according to the experiment. The wave is applied to the transmitter as a compression wave, and a displacement is outputted from the receiver. Notice that only the analysis results of 150 mm of distance between the transducers are shown because of the space of this article.

### Table 1 Analysis parameter of concrete

<table>
<thead>
<tr>
<th>Poisson ratio</th>
<th>Mass density (g/cm(^3))</th>
<th>Elastic modulus (N/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.3</td>
<td>mortar: 25,000 coarse aggregate: 50,000</td>
</tr>
</tbody>
</table>

2.3 INFLUENCE OF AGGREGATE DISTRIBUTION

It is impossible to grasp the distribution of coarse aggregates in an actual concrete structure. Prior to the analysis, it is necessary to evaluate the influence of the heterogeneity such as an aggregate distribution on the ultrasonic propagation. In this section, the elastic moduli of sound coarse aggregates and degraded ones are respectively set to 50000N/mm\(^2\) and 20000N/mm\(^2\) on the presumption that 25% of the whole coarse aggregates are degraded. Three patterns of random distribution of coarse aggregates are prepared using the program of a random number generation, and the ultrasonic propagation is analyzed for these three patterns of distribution under 150 mm of the distance between the transducers. A response waveform at the receiver is shown in Fig.6. The arrival time and amplitude of both the direct and echo waves are almost the same for all the patterns of distribution. Therefore, it is inferred that the propagation characteristic of the ultrasonic is hardly affected by the distribution of coarse aggregates, but that it is influenced by the volume fraction of coarse aggregates or the ratio of degraded ones.

2.4 INFLUENCES OF DEGRADATION ON ULTRASONIC PROPAGATION

1) Decrease of the elastic modulus of coarse aggregates

It is known that the strength and elastic modulus of the concrete structure decrease when microcracks occur around coarse aggregates due to the expansion of an alkali aggregate reaction or specific cracks grow due to their localization in a concrete structure. This study avoids the complicated modeling mentioned above, and makes much account of simple one. Thus, the elastic modulus of some coarse aggregates on their own is decreased so as to represent the reduction of the

### Table 2 Elastic modulus (case1)

<table>
<thead>
<tr>
<th>Analysis case</th>
<th>case2.1</th>
<th>case2.2</th>
<th>case2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (N/mm(^2))</td>
<td>40,000</td>
<td>30,000</td>
<td>20,000</td>
</tr>
</tbody>
</table>
elastic modulus around coarse aggregates. In this presupposed setting, the influence of the value of the elastic modulus on the ultrasonic propagation is discussed. The elastic modulus of the deteriorated element of the coarse aggregates is shown in Table 2. It is noticed that the elastic modulus of sound coarse aggregates is 5000N/mm², and that the deteriorated coarse aggregates account for 25% of the whole coarse aggregates. An example of the distribution of each element is shown in Fig.7.

The analysis response waveform is shown in Fig.8. Whereas the difference of direct wave is very small among the varied elastic moduli of deteriorated coarse aggregates, the echo wave arrives at the receiver late with a reduction in the elastic modulus of deteriorated coarse aggregates. Accordingly, it is clarified that the echo wave propagating inside a deteriorating material arrives at a receiver later than that inside a sound one.

(2) Influence of cracks occurring in concrete surface

As is shown in Fig.9, a number of lattice-shaped cracks occurred in the surface of experimental specimen. Especially, the cracks occurred densely around the receiver in case that the distance between transducers is 150mm. Its opening width is about 0.10mm to 0.35mm and is slightly larger than that of the cracks occurring in other places. Therefore, the influence of the cracks occurring around the receiver on the ultrasonic propagation is discussed.

First, an analysis is conducted under the assumption that a crack is located immediately above the receiver in the case of 150 mm of the distance between transducers (see, Fig.10). Crack depths are supposed to be 14mm and 28mm, and the influence of the crack depth on the ultrasonic propagation is examined. It is noticed that the crack occurring in the surface of concrete specimen is expressed by the insert of a notch in the surface on which one node of F.E. analysis is duplicated. Since there is an absence of the connection between the duplicated nodes, it is presumed that the crack is located closely to the surface inside the concrete specimen but is invisible in an actual concrete.

Crack is set to go around the circumferential direction of the specimen. Response displacement at the receiver is shown in Fig.11. In this case, there are two types of the ultrasonic waves; one reflects by the crack, and another diffracts at the tip of the crack. Since the receiver is located directly below the occurring crack, the wave diffracting at the tip of the crack is mainly measured by the receiver. Therefore, the arrival time of the diffracting wave at the receiver depends on the crack depth. Fig.11 also indicates that the arrival time of the direct wave becomes later as the crack gets deeper. The arrival time of the direct wave in the case of the occurrence of crack is different from that in a sound condition. On the other hand, the arrival
time of the echo wave in the case of the occurrence of crack is more or less same as that in a sound condition. As has discussed above, it is possible to determine the presence or absence of deterioration such as the existence of crack by means of the direct wave since the arrival time of the echo wave in the case of the occurrence of crack is different from that in a sound condition. In other words, it is possible to evaluate the degradation of specimen by the characteristic of direct wave. Next, the case (case 2.2) that a crack is located immediately below the receiver is additionally analyzed so as to examine the influence of crack location on the ultrasonic propagation. Case 2.1 is same as above case, 28mm of crack depth. Response displacement is shown in Fig.12. In the case of the crack located directly above the receiver, the wave diffracting at the tip of crack is received by the receiver, and in the case of the crack located directly below the receiver, the wave reflecting across the crack is received. Consequently, there are differences between the arrival times of the direct wave measured by the receiver as the crack location is changed.

As mentioned above, it is possible that a crack location is grasped by the difference of response waveform even in the case of invisible crack since the propagation waveform depends on the location of the crack and transducers. Moreover, it is expected that the existence or position of cracks are detected without the result in a sound condition since the response displacement at the receiver between the crack locations depends on the installation position of the receiver.

(3) Multiple deteriorations
The arrival times of the direct and echo waves of the experiment are drastically later than those of the analysis in a sound condition by comparing Fig.2 with Fig.12. According to the comparison, it is inferred that the phenomena such as the reduction of elastic modulus around coarse aggregates due to the occurring microcrack associated with the alkali-aggregate reaction and the phenomena such as the localized crack emanating from the microcracking area are multiply brought about. Thus, in this subsection, the analysis of multiple deteriorations which are the reduction of elastic modulus in degraded elements and the crack occurrence immediately above the receiver is carried on. It is noted that the position and depth of crack is same as those of case 2.1. It is presupposed that the deteriorated coarse aggregates account for 50% of the whole coarse aggregates, and that its elastic modulus is set to 20000N/mm². Response displacement is shown in Fig.13. Comparing the analysis result (Fig.13) with the measured data (Fig.2), both waveforms are mostly similar. There is, however, a difference between the waveforms of the analysis and measurement from 100 to 200 micro seconds. The difference can be attributed to a number of cracks occurring inside the experimental specimen. Therefore, it is necessary to discuss such cracks occurring inside the specimen in the future.

3. CONCLUSIONS
In this study, three-dimensional finite element analyses are conducted for the concrete in which alkali-aggregate reaction is accelerated so as to discuss the application of
the echo method to the degradation evaluation of heterogeneous material. Microcracks occurring around expanded coarse aggregates due to alkali-aggregate reaction and specific cracks emanating among the microcracks due to localization are taken up as deterioration.

The elastic modulus of some coarse aggregates on their own is decreased as for the occurrence of microcracks, and a crack is set near by the surface of analysis model as for the localized crack. Since the arrival time of echo wave in a degraded condition is later than that in a sound condition, it is possible to evaluate deterioration by comparing the current data with past one of periodic inspection in a sound condition. However, the evaluation is difficult without such past data. On the other hand, in the case that there are localized cracks, the position of the cracks can be presumed by the change of response displacement at a receiver depending on the geometric relations between the receiver and the cracks. In this case, the measurement data in a sound condition or the previous one are not necessary. Therefore, the crack position can be estimated by the response displacement with changing the installation position of transducers if the localized crack grows close to a specimen surface. From mentioned above, it is indicated that the deterioration evaluation is possible even if a transmitter and a receiver are set on the same side of specimen surface. However, it is not enough to lead this conclusion since deterioration situations are modeled in an extremely simple method. As for future works, it is necessary to reflect more deterioration phenomena on analyses, and to discuss an ultrasonic propagation in detail through the analyses.

REFERENCES

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